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6 ENHANCING PERCEPTIBILITY OF BARELY PERCEPTIBLE TARGETS.

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SUMMARY

We have discovered a class of powerful procedures for improving perception of targets obscured in dim, briefly-flashed, or noisy images. These procedures require no precise knowledge of where the targets appear in the image nor are they dependent on what the targets look like. They involve adding particular kinds of spatial and temporal contexts to the obscured image. Perception then improves strikingly.

During the contract year, we found that perceptual accuracy could be improved by as much as 20% to 100% when 1) Individual picture elements in a digitized noisy photograph (of a face, vehicle, etc.) were flickered; 2) Additional noise was added to the already noisy photograph and the individual picture elements were flickered; 3) Fragmented images blocked in the middle by a horizontal black bar were flickered or moved; 4) Observers trying to pick out the brightest of a set of dots saw the dots rotating within a sphere rather than remaining stationary; 5) Auxiliary lines were combined with a small target line segment to yield perception of a three-dimensional object; 6) These auxiliary lines surrounded but did not combine with or touch the target line; 7) Auxiliary lines alternately created either a distinct figure or background within which the target appeared. This last may be our most striking finding so far. It involves adding a simple line drawing to an image; it more than doubles the d' for discriminating the orientation and detecting the presence of a small diagonal target line within that image.

The facilitatory treatments listed above may seem diverse and also paradoxical, since each adds noise or seemingly irrelevant detail to the image. In fact, however, they were all developed from a single basic principle of visual system functioning and their effectiveness apparently stems from this principle. The visual system tends to construe patterns as pictorially meaningful, and when it does, peripheral sensory mechanisms sharpen and clarify their response. Each of our manipulations added spatial and/or temporal contexts that imparted meaning to an image or that augmented the effectiveness of mechanisms for extracting meaning. For example, given the image of a single diagonal target line, adding auxiliary lines can create the perception of figure against background and enhance detection of the target line when it falls within the figure region. We can also enhance the target line when it falls within the background region. Here we blur the target, thereby favoring low frequency response which is more sensitive to background than to figure.

A major virtue of our enhancement procedures is that targets do not have to be restricted to a fixed location nor does the exact location have to be known or discovered beforehand. This is obvious in the case of temporal manipulations, but we have found this year that it applies to our spatial manipulations as well. Merely having the target within a broad region of the image perceived as figure or ground--regardless of whether that region is in the fovea or in the periphery--can improve perception markedly.

We found a similar lack of constraint on the types of images amenable to our enhancement procedures. Our procedures worked with such dissimilar images as randomly placed dots and short vectors, small diagonal line segments, fragmented forms, and digitized photographs of faces, roadways, tanks and trucks obscured by various types of noise.

Our work during this contract year suggests that we can develop a large, varied, and flexible stockpile of image enhancement techniques. There are many different ways of imparting visual meaning to an image. There are many different image types amenable to enhancement. Our findings may prove applicable to such disparate situations as picking up key words or sentences in documents, spotting faces in a crowd, identifying objects in aerial reconnaissance, underwater photography and surveillance and badly damaged photographs, recognizing marginal video and facsimile transmissions, and interpreting camouflaged images.

ENHANCING PERCEPTIBILITY OF BARELY PERCEPTIBLE TARGETS
FINAL TECHNICAL REPORT

During the contract year, we found that perceptual accuracy could be improved by as much as 20% to 100% when we applied the manipulations described below.

Four of the facilitatory manipulations were temporal and three of them were spatial. The temporal manipulations and then the spatial manipulations are described in turn.

TEMPORAL MANIPULATIONS

WHAT WE HAVE FOUND THIS YEAR

- 1.) Multiphase sawtooth flicker: Flickering individual picture elements in a digitized noisy photograph markedly improves recognition.

Figure 1 shows a digitized image of a face obscured by 80% noise:

Figure 1



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The underlying face emerges in dramatic clarity and the noise drops out or becomes much less visible when we subject this noisy image to multiphase sawtooth flicker (Weisstein & Genter, Note 1; Genter & Weisstein, 1980a and b, and Note 2). In this kind of flicker each picture element is flickered independently with its brightness increasing over the course of about 20 frames until it reaches maximum intensity. Then it jumps back to black and increases again.



Figure 2

Indeed, when observers were asked to identify which of 15 different photographs of male faces taken from a 1972 college yearbook was the one presented, and these faces were obscured by noise in the same way as the face above (Genter & Weisstein, Note 2), observers were more than twice as accurate when the faces were flickered as when they were presented statically. Static recognition accuracy was 45%; under multiphase sawtooth flicker, at a rate of about 2 Hz, accuracy rose to 96%.

- 2.) Multiphase sawtooth flicker with additional noise: Perception is often further enhanced when additional noise is added to an already noisy photograph and the individual picture elements are flickered.

The noise in Figure 1 was linearly added to a high contrast digitized photograph in modulo 256 arithmetic ('wrap noise'--when the noise added drives a picture element past the ceiling it jumps back to zero and increases again from there. The procedure is described in Genter & Weisstein, Note 2). We also degraded clear images by imposing non-linear types of noise (e.g. 'clip' noise, where the added noise is permitted only to drive a picture element up to a ceiling (white) or down to a floor (black)). When these noisy pictures were subjected to multiphase sawtooth flicker, there was some enhancement with 'clip' types of noise, but the enhancement was not as good as with the 'wrap' noises. However, when we added 'wrap' noise to an image already obscured by 'clip' noise and then flickered individual picture elements, enhancement again improved dramatically.

Figure 3. An image obscured by 'clip' noise. When flickered, there is not as much enhancement as with 'wrap' types of noise.



Figure 4. 'Wrap' noise is added to an image obscured by clip noise and the individual picture elements are again flickered. The enhancement produced is much better!

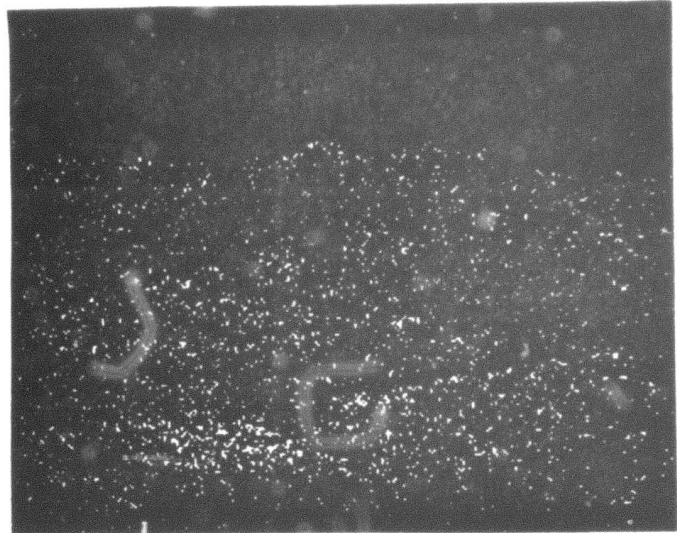
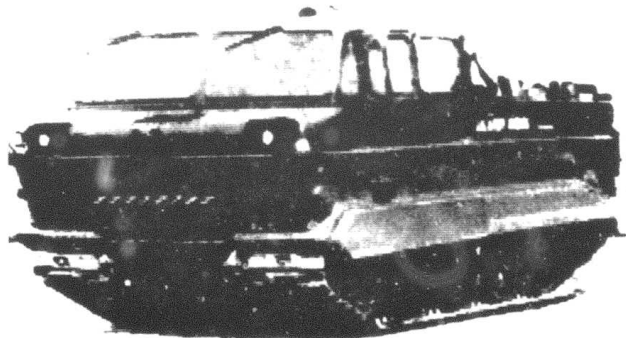


Figure 5. The underlying image.



A possible explanation for this paradoxical finding comes from pilot studies that show better enhancement when individual frames within a flicker cycle change steadily rather than infrequently and abruptly. Steady change may enable visual temporal integrating mechanisms to extract visual meaning from a sequence of frames more effectively. 'Clip' types of noise mean that many elements (those at the ceiling) simultaneously undergo an abrupt change. With 'wrap noise' fewer elements drastically change their brightness from one frame to the next. Thus, although the static images appear equally obscured, the addition of wrap noise to an image obscured by clip noise forces a steadier change in the sequence of frames, and this may account for the improved picture recognition. (A demonstration of this is on the video tape sent 3/23/81).

- 3.) Object completion: Flickering or moving fragmented images blocked in the middle by a horizontal black bar produces completion across the blocked region.

A sequence is presented consisting first of this image:

Figure 6. Fragments of
a boy on a tricycle.



Then the middle section of the image is blocked by a horizontal black bar:



Figure 7.

and finally, the image flickers or moves sideways while the bar remains stationary.

When the image is thus flickered or moved, 'phantom' blobs and picture fragments are seen dimly moving or flickering within the limits of the bar as if the bar were partially transparent (Brown, Weisstein & Genter, 1980, 1981).

In the above sequence, observers are asked to describe their perceptions during presentation of the first unblocked image. About half of them report seeing a boy on a tricycle. The others report seeing only meaningless fragments. When the black bar blocks the image, those who see the boy on a tricycle subsequently see the moving 'phantom' blobs and figure fragments in greater strength and for a longer period of time than those who did not see it. In addition, they also see the phantoms as part of the contours of the boy on the tricycle rather than just as fragments.

At specific rates of flicker (pilot studies indicate the rates are between 1 and 5 Hz), figural information may be preferentially filled in across noisy or nonmeaningful gaps. This may be a contributing factor in the enhancement obtained with the multiphase sawtooth flicker described above, as well as with other flicker procedures. We are further investigating the temporal and figural properties of phantoms and other motion-generated completion phenomena (Genter & Weisstein, 1981; Brown, Genter & Weisstein, 1981; Klymenko & Weisstein, Note 3).

- 4.) Observers trying to pick out the brightest of a set of dots do better when they see the dots rotating within a sphere rather than remaining stationary.

These randomly placed dots are steadily presented on a computer scope face. One of the dots is brighter than the rest. We give observers six seconds to spot the brighter dot. Accuracy is about 64%.

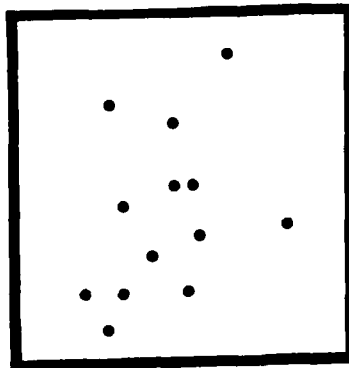
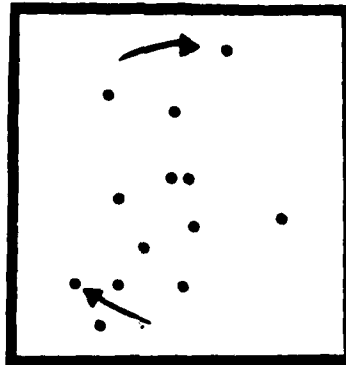


Figure 8.

Then the dots are moved so that they appear to be rotating inside a transparent sphere. This type of computer-driven display gives rise to a compelling illusion of depth (e.g., see Petersik, 1979). Again, we give observers 6 seconds to spot the brighter dot.

Figure 9.



This time, accuracy for the brighter dot jumps up to 87% (Weisstein & Genter, Note 4).

In our experiment, observers saw a display of 45 dots. One of them was brighter than the others. Some of the dots simply changed position randomly from frame to frame. (The percentage of dots that moved randomly varied in different conditions from 9% to 91%.) The rest of the dots either stayed put, or moved as if they were on the inside of a sphere. Mean accuracy for spotting the brighter dot is shown in the table.

WHEN THE BRIGHTER DOT WAS:	IT WAS ACCURATELY IDENTIFIED:
Moving randomly	51% of the time
Not moving	64% of the time
Moving in depth	87% of the time

(A video tape that includes similar enhancement with rotating short vectors was sent 11/23/80. The table updates results reported in Weisstein, Note 5.)

DISCUSSION OF TEMPORAL MANIPULATIONS

The rule for augmenting meaning-extracting temporal response in the manipulations above stemmed from our initial finding that visual response is faster to meaningful parts of an image (Weisstein, Note 5; Weisstein & Genter, Note 1; Williams & Weisstein, 1981; Genter & Weisstein, Note 2). This suggested to us that we might be able to enhance images by creating a sort of temporal 'filter'. Since the faster response apparently conveys the meaningful parts of an image, at relatively rapid rates of motion, flickering, or sequencing of an image, only the meaningful parts of an image should reach perceptual threshold.

The 'filter' appears to be working. We flickered noisy photographs at a rate which we previously found to produce the largest advantage for object-like patterns over flatter patterns; we flickered fragmented images blocked by a horizontal black bar at comparable rates; and we added noise to photographs already obscured by different kinds of noise in order to make the sequence of frames in a flicker cycle change steadily rather than infrequently. Each manipulation improved perceptual accuracy.

SPATIAL MANIPULATIONS

BACKGROUND

We now turn to facilitatory spatial manipulations. It is useful to begin with a brief history of the discovery which led to the research described here: 'object-superiority'.

In 1974, Charles S. Harris and I found that we could dramatically enhance observers' performance on the simple task of identifying which one of four barely perceptible, briefly flashed line segments was present;

Figure 10



by adding to those line segments a fixed set of auxiliary lines:

Figure 11



which when combined with each target line, yielded perception of a unified, three dimensional object.

Figure 12



Not just any auxiliary lines could be added, however. The auxiliary pattern had to combine with the diagonal target lines to yield perception of what looked like an object. If the auxiliary pattern combined with the target lines to yield flatter, less object-like patterns such as in the figure below, accuracy was not enhanced.

Figure 13



WHAT WE HAVE FOUND THIS YEAR

5.) Three-dimensionality appears to be what counts in 'object-superiority'.

During the contract year we continued to investigate precisely what aspects of patterns are responsible for the accuracy advantages found in 'object-superiority'. In two studies (Weisstein, Williams & Harris, Note 6; Lanze, Weisstein & Harris, Note 7) we had subjects rate eight patterns for perceived three-dimensionality, perceived connectedness, and perceived 'structural relevance' of the target line to the pattern. In the first study we found that accuracy in the identification task bore little or no relationship to judged connectedness but was highly correlated with perceived depth and structural relevance. However, perceived depth and structural relevance were also highly correlated with each other. In the second study, when we varied three-dimensionality and structural relevance independently, we found that accuracy was negatively correlated with structural relevance ($r = -.28$) while continuing to be highly and significantly correlated with the judged depth of the pattern ($r = +.78$).

6.) The auxiliary lines do not have to combine with or touch the target line in order to enhance it.

The Lanze, Weisstein and Harris study (Note 7) also showed something else: when the target line was placed near the side or in the middle of the patterns

and did not touch or combine with them, accuracy was nonetheless 20% higher for the pattern judged highest in perceived depth than for the flatter patterns. This finding greatly increases the potential applicability of facilitatory spatial manipulations, since it indicates that the target does not have to be in a precise location relative to a spatial manipulation in order for enhancement to occur.

- 7.) Auxiliary lines alternately creating either a distinct figure or background within which the target appears can double discrimination or detection accuracy for the target.

An even more striking demonstration of facilitatory spatial enhancement independent of location occurred in our next study.

As in object superiority, we began by asking observers to tell us which of these two line segments has been flashed (or, in an alternate task, whether or not a line segment has been flashed). We find that d' is about .7 for discrimination and about .5 for detection.

Figure 14.

Next, we add Figure 15, which can alternately be seen as a vase or two faces.

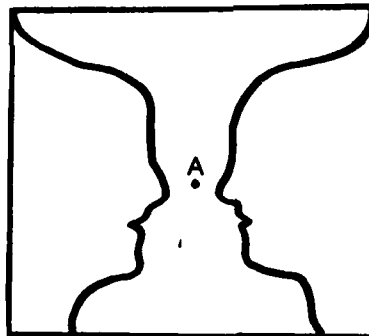
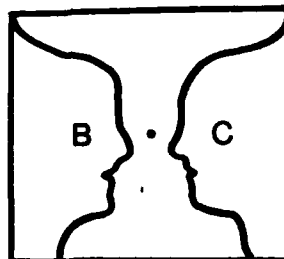


Figure 15.

We asked observers to press a key whenever they see the pattern as a vase. When the key is pressed, a target is flashed at A, the fixation point. The d' jumps to about 1.5 for discrimination and to about 1.3 for detection.

Targets presented off-fixation. The same result holds when the side regions are seen as figure (faces), and the target is flashed at B or C (Figure 16). Accuracy is again twice what it is when the target is flashed at B or C in isolation (Wong & Weisstein, 1981, and Note 8; see especially the test which rules out eye movements as an alternate explanation for these results).

Figure 16. When the pattern is seen as two faces, and the target is flashed at B or C (the fixation point remains in the middle) accuracy is again twice what it is when the target is flashed at those locations in isolation, without the added profile lines.



It should be noted that the auxiliary lines must create a perceptually distinctive figure and ground. When the target is flashed along with these rectangles:

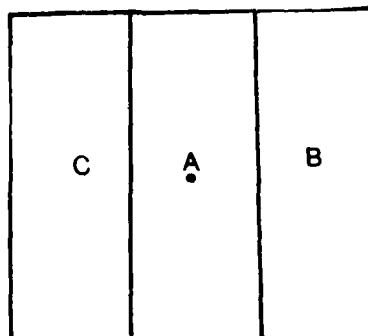


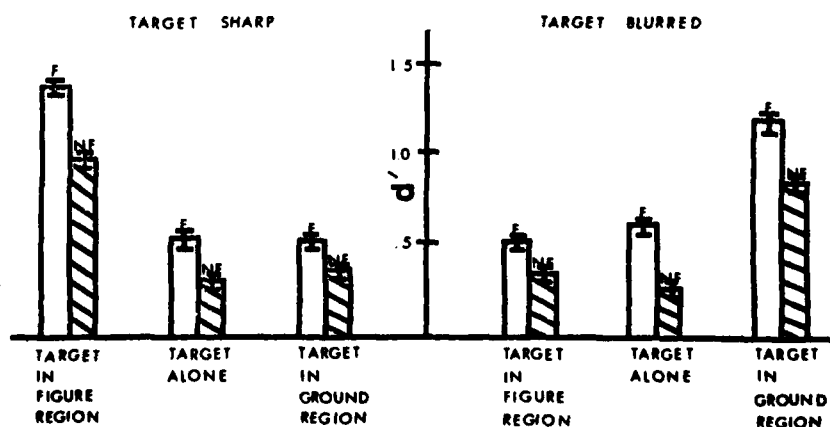
Figure 17

and observers are instructed to see the center as figure and the sides as ground there is a negligible change in accuracy from the target flashed in isolation.

Background can also be made into an enhancing region. We can reverse these results so that the target line is seen better on the background than either on the figure or when flashed alone. To do this, we blur the target line and flash it against ground, i.e., at A when the pattern is seen as faces or at B or C when the pattern is seen as a vase. Paradoxical as it may seem--blurring a target usually decreases perceptual accuracy for it--detection is now twice as good when the target is seen in the ground regions than when it is flashed in isolation or seen in the figure regions. Again, the enhancement occurs regardless of whether the target is flashed at or off fixation. Figure 18 shows the results.

TARGET DETECTED

Figure 18. When the target line is in focus, it is detected best in the figure region. (Left panel). When the target is blurred, it is detected best in the ground region (right panel). Open bars represent the target flashed at fixation (A). Striped bars represent the target flashed off-fixation (B and C).



By blurring the target we favor low frequency response which is more sensitive to background than to figure.

Generality of these effects. These results may prove to be our simplest and most generally applicable to date. They suggest the following procedure for maximizing the detection of an unknown target. 1) Add auxiliary lines that divide an image into figure and ground. 2) Search for the target when the central region is seen as figure and again when the flanking regions are seen as figure. 3) If the target has not yet been found, blur the image, and search the background regions. Thus, wherever a target is located, our results suggest that in one of these conditions, an observer ought to be able to spot it more than twice as accurately as without the auxiliary lines.

SUMMARY OF WHY WE FOUND WHAT WE DID THIS YEAR

The new methods we have found for enhancing perception are illustrations of a distinctive approach to image enhancement. The approach, stated briefly, is to improve an obscured or noisy image by adding particular kinds of spatial and temporal contexts to it.

This approach runs counter to standard image enhancement procedures because it lowers, rather than raises, signal-to-noise ratios. For instance, in some of the examples above, temporal dynamics--flicker, motion, a sequence of changing images--are added to an obscured or difficult image. Adding such temporal complications to an already barely visible image might be expected to interfere with identification. But surprisingly, the correct temporal manipulation leads to the emergence of the image or its parts in sharper perceptual clarity.

Why would adding certain types of temporal and spatial 'noise' to an already obscured signal improve its clarity? The answer lies in a general principle of visual response that has emerged from our investigations. It has long been suspected (by the Gestalt psychologists and even earlier investigators--e.g., see review by Hochberg, 1979) that the visual system is particularly responsive to meaningful objects and events. Our research has found such enhanced responsiveness. When a pattern is seen as three-dimensional or otherwise pictorially meaningful, sensory mechanisms sharpen and amplify their response. Visual system response becomes stronger and faster. The efficiency of temporal integration increases, thresholds go down, and the number and type of active mechanisms increases. Increased activity even extends to mechanisms that do not receive direct retinal stimulation: observers see missing parts of forms in regions that are actually receiving uniform stimulation (p. 6 & 7). In seeking meaning, the visual system performs its own internal image enhancement--extracting coherent images and rejecting noise.

Building on this discovery that meaning is a primary ingredient of seeing an image clearly, our approach makes use of spatial and temporal contexts that help the visual system pick up meaning in the image. Two stages are involved. First, we impose temporal and spatial pictorial meaning on an image. Second, we attempt to amplify the output of those sensory mechanisms that change their activity in response to meaning.

Our aim this contract year was to see the extent to which our approach would work both inside and outside specific laboratory situations, and whether it would be robust, effective, and generally applicable. To test this, we studied a range of phenomena and types of images, such as multiphase flicker of faces, motion-in-depth of random dots, object completion of fragmented forms, figure/ground organization of diagonal line segments. We have been looking for big

effects--20%-100% improvement in perceptual accuracy.

Our initial efforts have been most successful. Our procedures are working and the effects are big. In the next two years we hope to develop these effects into working image enhancement procedures, determining their range, limits and optimum parameters, showing how, why, and for what applications they work. We will also continue to identify the ways in which sensory mechanisms sharpen and clarify the meaningful components of images. On the basis of this knowledge, we can improve our procedures still more or possibly develop new and even better ones. Our success so far leads us to believe that we may be able to generate a battery of procedures that can enhance images or parts of images in an extensive range of applications.

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+ Indicates that the paper is already on file at DARPA.

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